

Novel Paradigms and New Options @ ATF-II

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Outline

- *Personal Experience at ATF-I*
- *Wake Amplification*
- *Optical Injector*
- *Channeling Radiation in Vacuum*

Personal Experience @ ATF-I

- During the early 90's we have been investigating two-stage traveling wave amplifier. The two stages were severed by a lossy-section.
- Decelerating force exerted by the wake-field on the generating bunch depends on the conductivity.
- Naturally the question was raised what happens if rather than a passive medium, we employ active medium

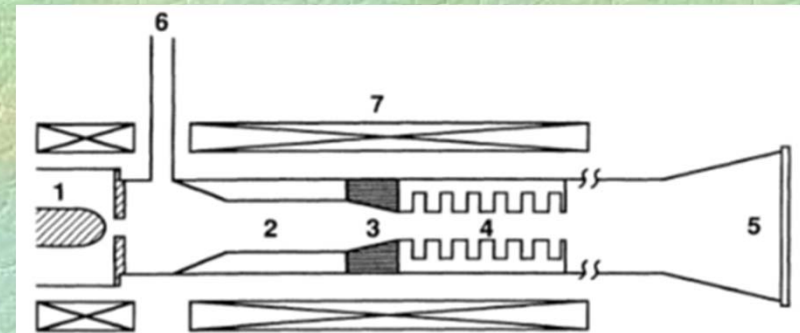
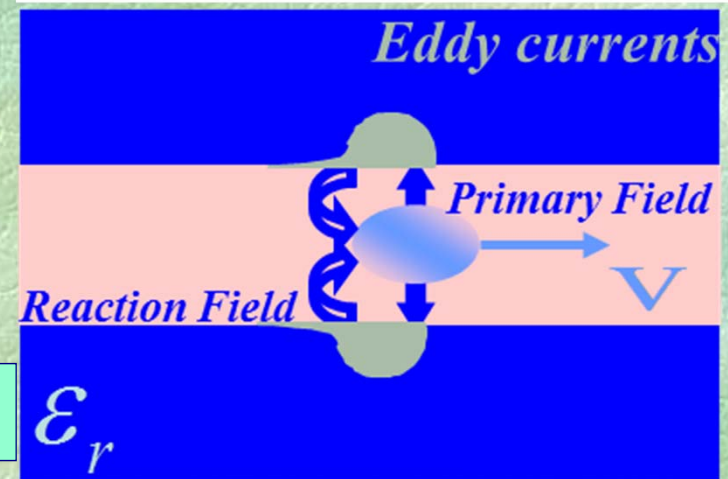
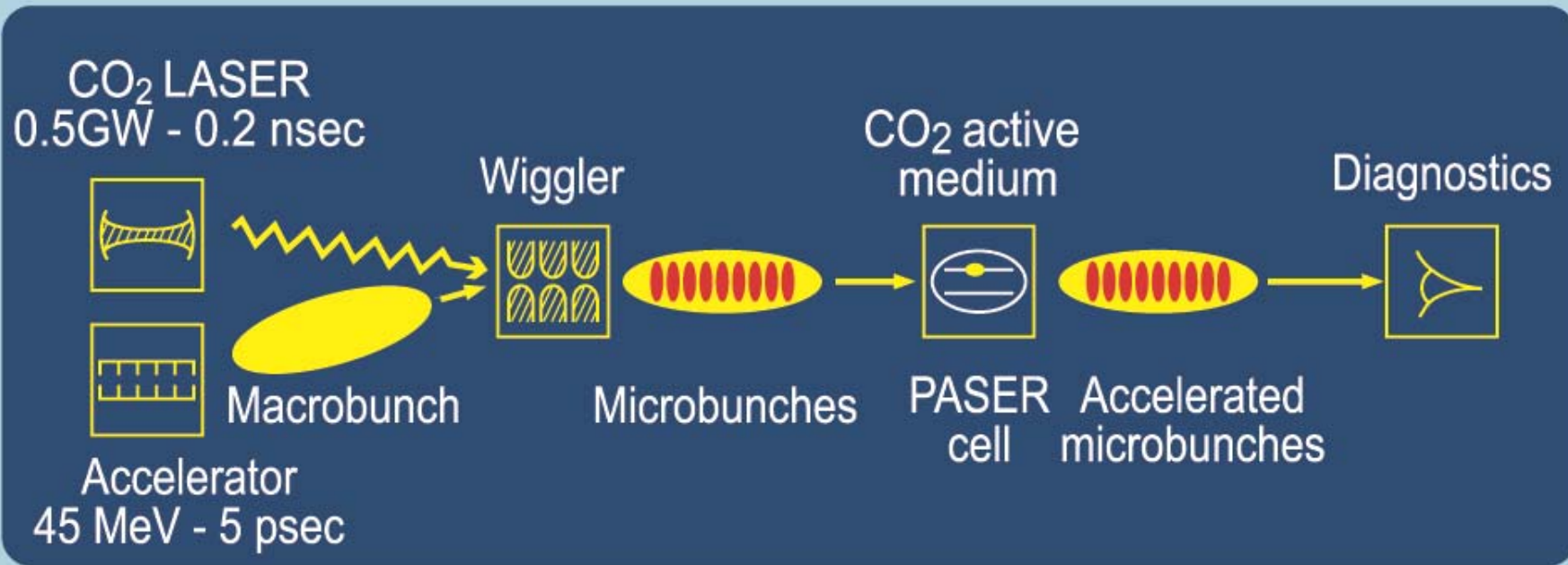


FIG. 2. Schematic showing the assembly of a two-stage severed amplifier. The first stage uses a dielectric loaded amplifier and the second stage a 10 period narrow band (low group velocity) structure. (1) Electron beam diode, (2) dielectric first stage, (3) silicon carbide sever, (4) narrow band structure, (5) output horn, (6) input waveguide, (7) magnetic field coils.



Personal Experience @ ATF-I

ATF-I provided a unique opportunity due to availability of intense laser beam and 45MeV electron beam. Essential set-up:



Personal Experience @ ATF-I

PRL 97, 134801 (2006)

PHYSICAL REVIEW LETTERS

week ending
29 SEPTEMBER 2006

Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation

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(Received 4 June 2006; published 28 September 2006)

We report the first experimental evidence for direct particle acceleration by stimulated emission of radiation. In the framework of this proof-of-principle experiment, a 5 MeV electron macrobunch was modulated by a high-power CO₂ laser and the resulting microbunches were accelerated in a gas mixture. The emerging microbunches experienced a 0.15% relative energy spread over a 40 cm long interaction region. According to our experiment, the electrons have gained more than 200 keV each, implying that such an electron-electron collision is of the second kind.

DOI: 10.1103/PhysRevLett.97.134801

*ATF's success,
is our success !!*

PHYSICAL REVIEW LETTERS

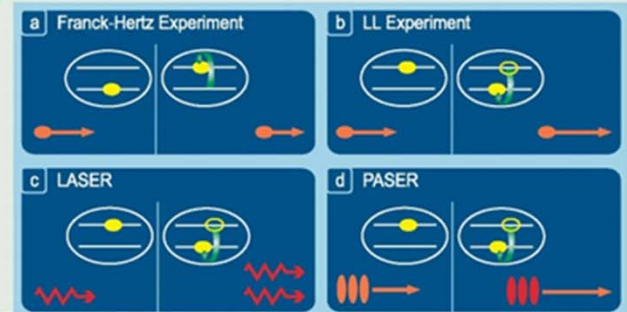
Articles published week ending
29 SEPTEMBER 2006

Volume 97, Number 13

NewScientist

September 30-October 6, 2006

Lasers inspire new way to get electrons pumped up



NATURE|Vol 443|21 September 2006

That's no laser, it's a particle accelerator

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Wake Amplification

Limitations and solutions

- **Problem:** PASER as single-particle process, is competitive *below* Cherenkov condition otherwise, the deceleration associated with the latter dominates.
- **Solution:** operate *above* Cherenkov, rely on collective amplification by the active medium – like in a LASER except that the homogeneous wave is replaced by a wake.
- **Problem:** low gain $\alpha = 1 \left[\text{m}^{-1} \right]$
- **Solution:** operate near the Cherenkov “cut-off”

$$\bar{\varepsilon} \equiv \varepsilon_r - \beta^{-2} \sim 0$$

Wake Amplification

Cherenkov in passive medium

- *Boundless case*

$$A_z \propto \exp \left[j\omega \left(t - \frac{z}{v} \right) \right] H_0^{(2)} \left[\sqrt{\epsilon_r - \beta^{-2}} \frac{\omega}{c} r \right]$$

- *Confined in a cylindrical waveguide*

$$\omega_s = \frac{c p_s}{R_w} \frac{1}{\sqrt{\epsilon_r - \beta^{-2}}} ; \quad s = 1, 2, \dots, \infty, \quad J_0(p_s) = 0$$

- Near *Cherenkov cut-off*, eigen-frequencies are elevated.

Wake Amplification

Cherenkov in Active Medium – bounded case

- Dielectric coefficient

$$\varepsilon(\omega) = \varepsilon_r + \frac{-2c\alpha\Delta\omega\sqrt{\varepsilon_r}}{\omega_0^2 + j\omega\Delta\omega + (j\omega)^2}$$

- Resonant eigen-frequency

$$\omega_- = \omega_0 + j\frac{\Delta\omega}{4} \left[1 - \sqrt{1 + 16\frac{c}{2\Delta\omega} \frac{\alpha}{\varepsilon_r - \beta^{-2}}} \right] \equiv \omega_0 + j\delta\omega_-$$

- Example based on [D. Haberberger, S. Tochitsky, C. Joshi, Opt. Express 18 \(2010\)](#)

$$\Delta\omega \simeq 2\pi \times 37 \times 10^9, \bar{\varepsilon} = 1.42 \times 10^{-3}, \alpha = 1 [\text{m}^{-1}]$$

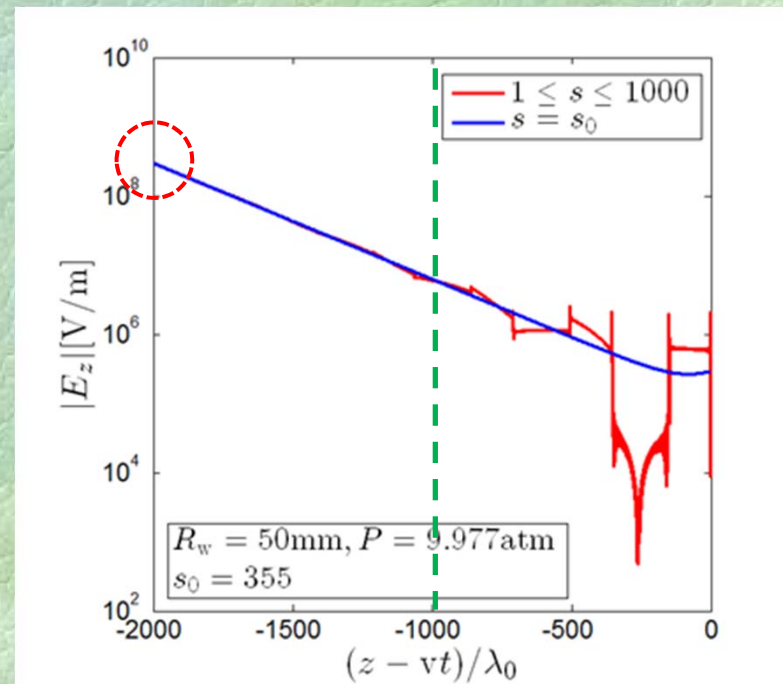
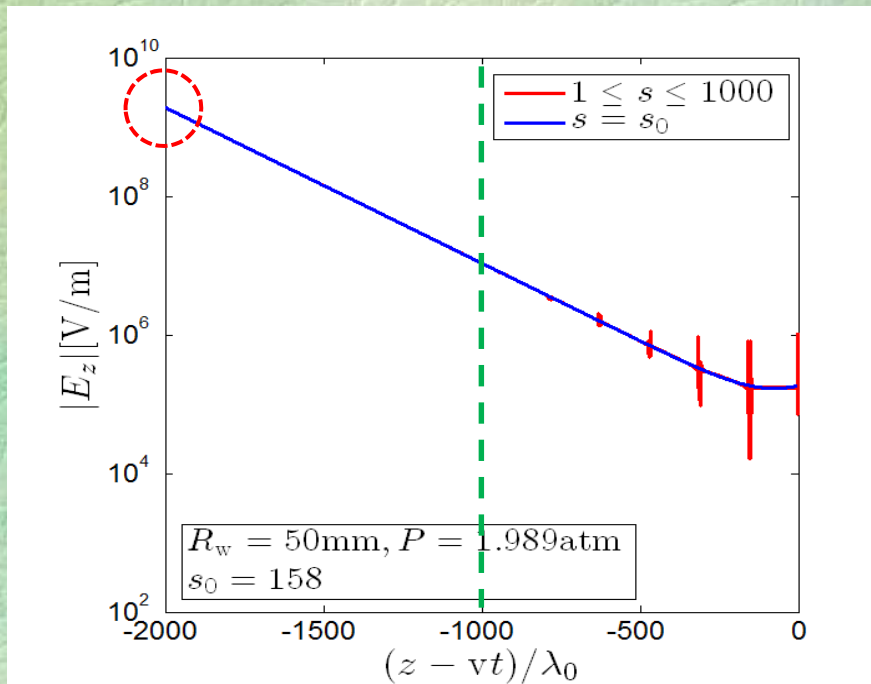
- Three orders of magnitude *gain-enhancement*

$$\alpha_{\text{eff}} = \frac{\delta\omega_-}{c} \simeq 471 [\text{m}^{-1}]$$

Wake Amplification

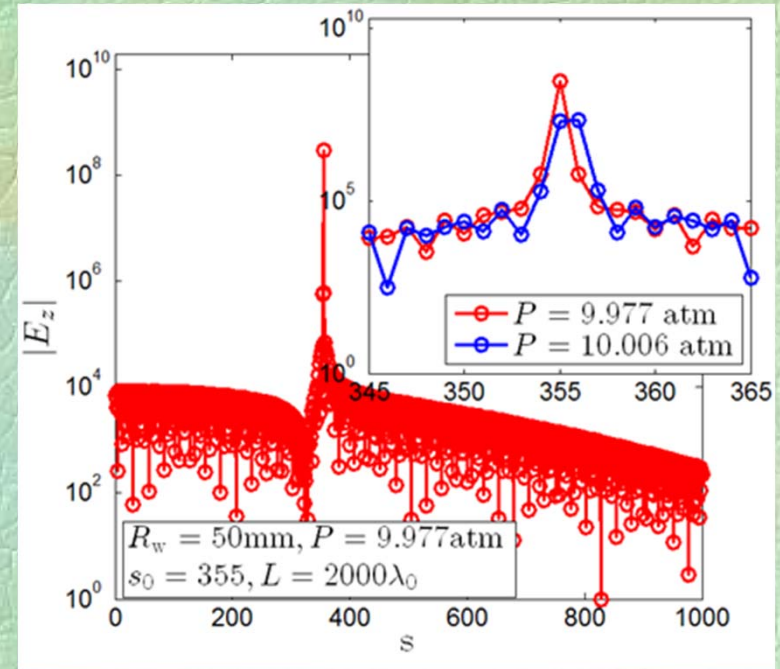
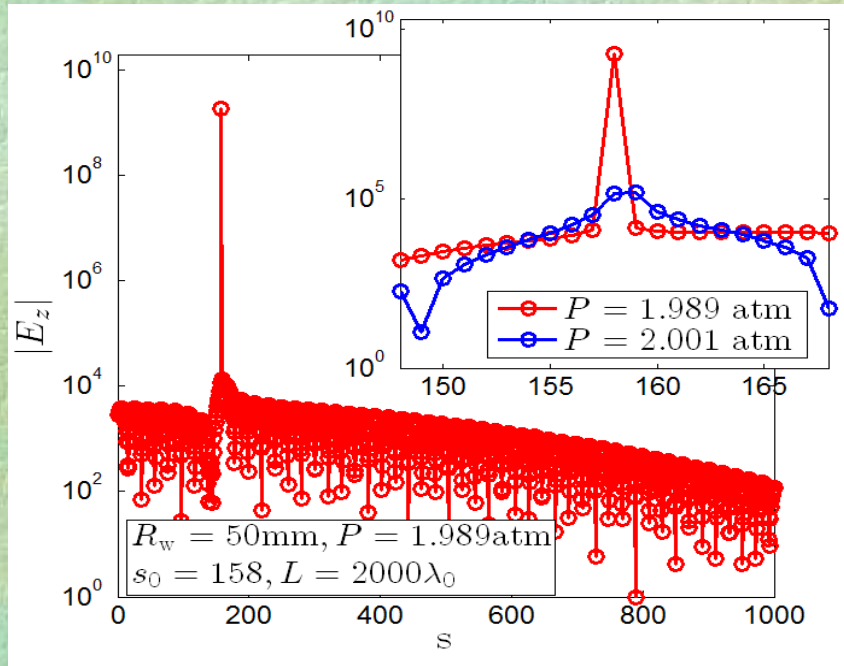
Resonant eigen-mode on axis

$$\frac{E_z(z, t)}{E_s^{(\text{trigger})}} \simeq \left\langle \cos \left[\omega_0 \left(t - \frac{z - z_i}{v_{\text{trigger}}} \right) \right] \exp \left[\alpha_{\text{eff}} c \left(t - \frac{z - z_i}{v_{\text{trigger}}} \right) \right] h \left(t - \frac{z - z_i}{v_{\text{trigger}}} \right) \right\rangle_i$$



Resonant mode dominates after 1000λ

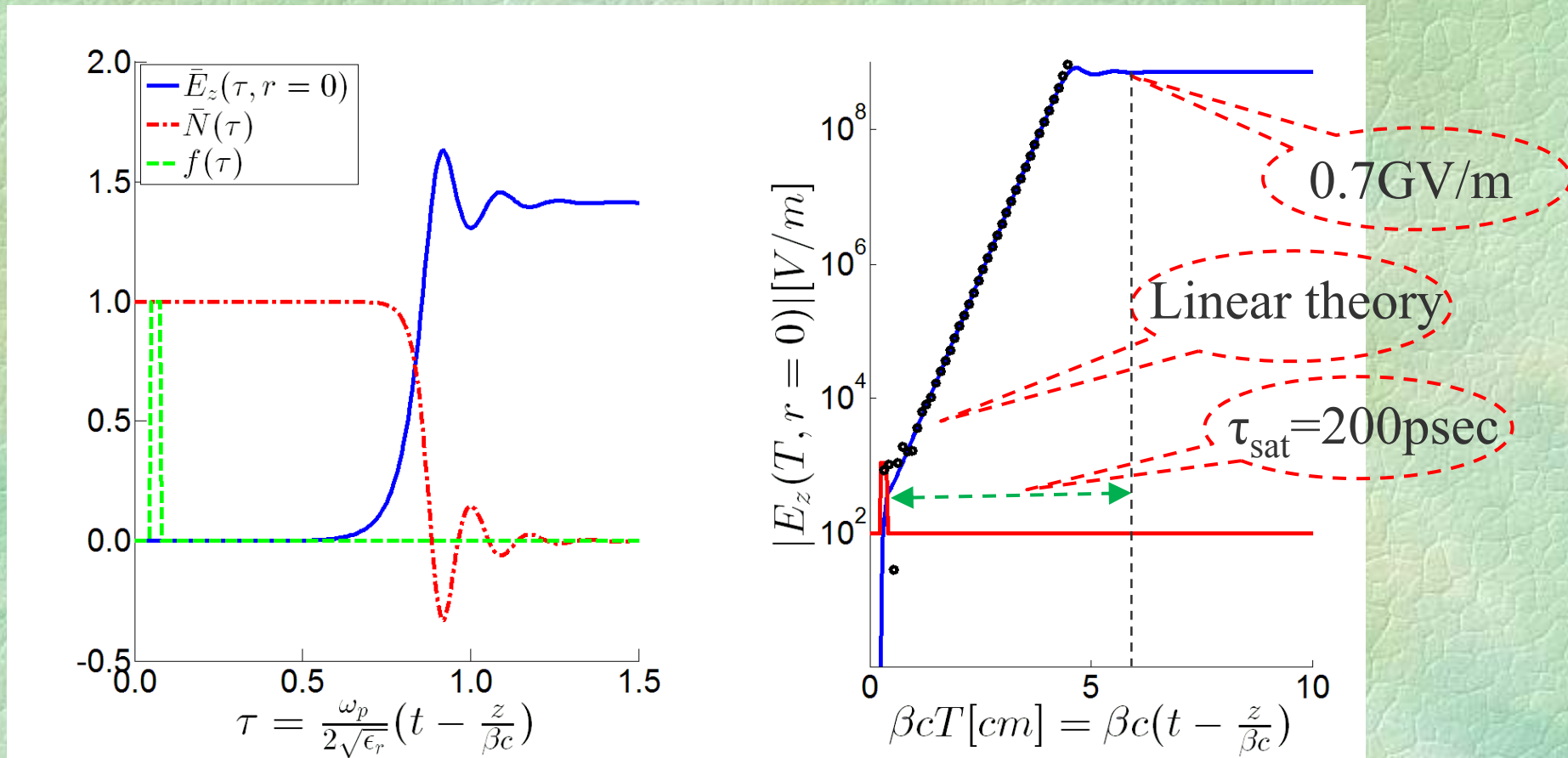
Wake Amplification - Linear



- Gradient spectrum of 1000 Bessel harmonics at four pressures
- 3-4 orders of magnitude difference between amplitude of resonant mode and all the others.
- off resonance the difference is less pronounced

Wake Amplification - Saturation

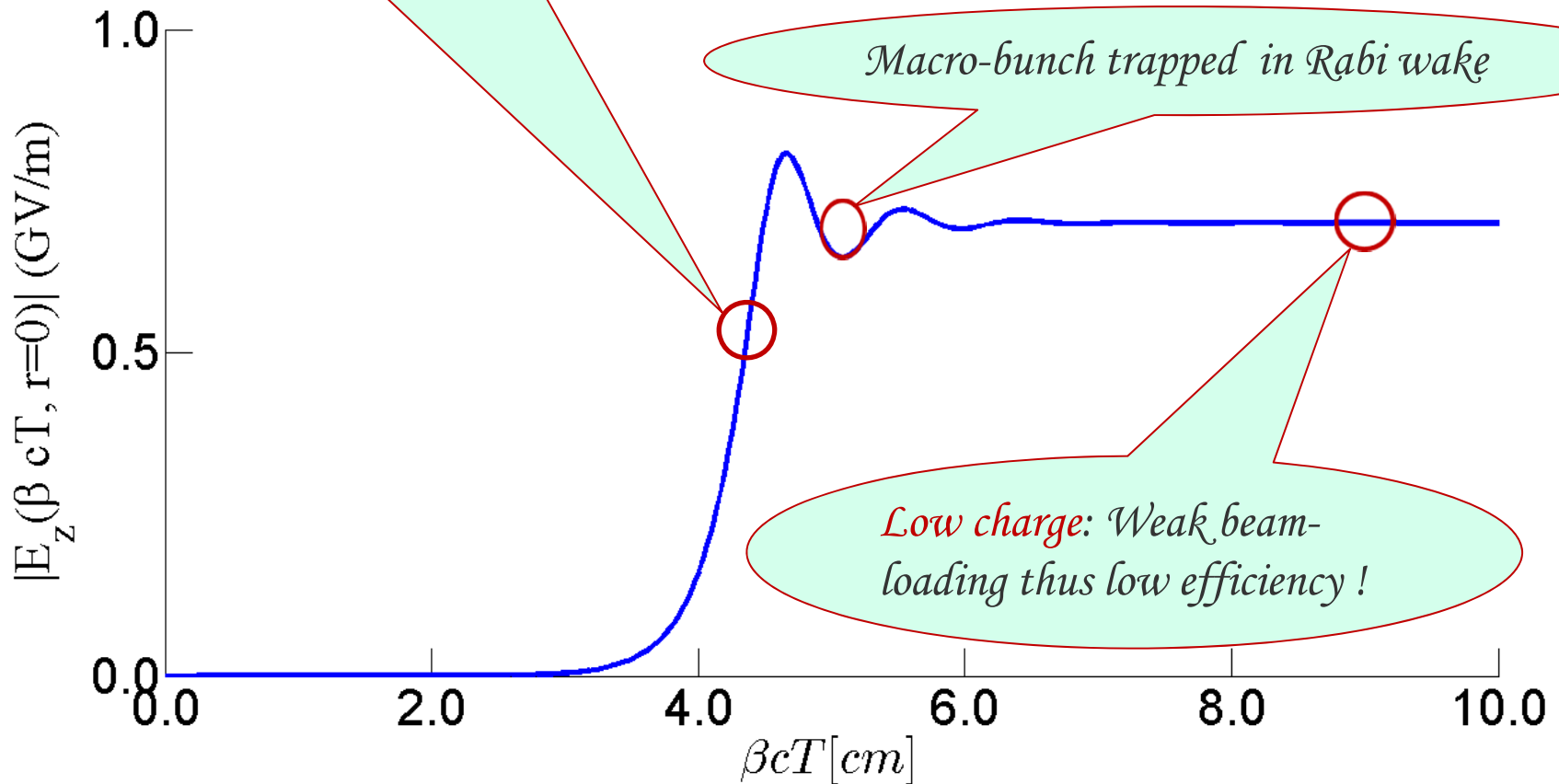
Wake and population inversion dynamics – slowly varying amplitude



Wake reaches saturation on *less than 1 nsec time scale*

Wake Amplification – Acceleration options

High charge: Exponential growth compensates the beam-loading



Wake Amplification – Two-Beam Acc.

Essence of the proposed paradigm:

- Driving beam replaced by *trigger train of micro-bunches* (mB).
- Trigger beam does not carry the energy required for acceleration
- It excites a *quasi-coherent Cerenkov-wake* that is *amplified by the medium*.
- It is the latter that *contains the energy* necessary for acceleration.
- As the medium is *depleted*, the field reaches saturation and this is where the train of bunches to be accelerated is placed.



Wake Amplification - TBA

Essence of the proposed paradigm (cont.):

- Depletion occurs on time scale of *less than 1 nsec*.
- Rep-rate determined by *luminosity* - 10^{14}sec^{-1}
- At optical scale, typically, one mB contains up to 10^4 electrons.
- Trigger train may contain 10^3 mB's thus, the *rep-rate* higher than 10MHz is required.



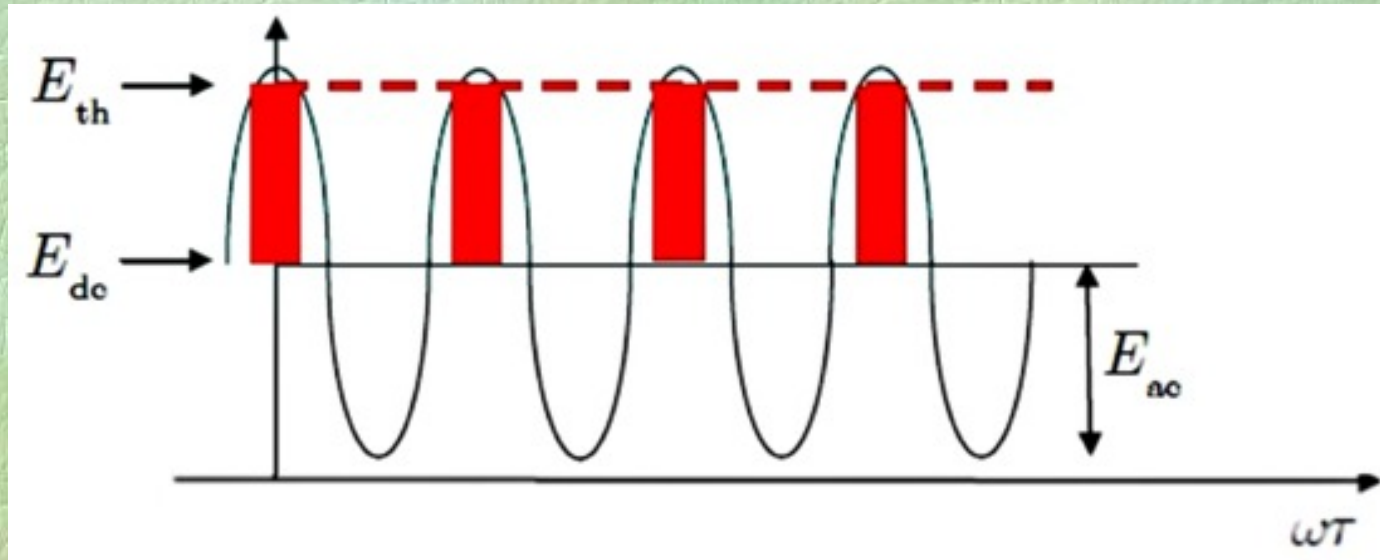
Outline

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- *Wake Amplification (TBA)*
- *Optical Injector*
- *Channeling Radiation in Vacuum*

Problem: How do we generate a train of *density modulated* micro-bunches of electrons with spacing on the optical scale?

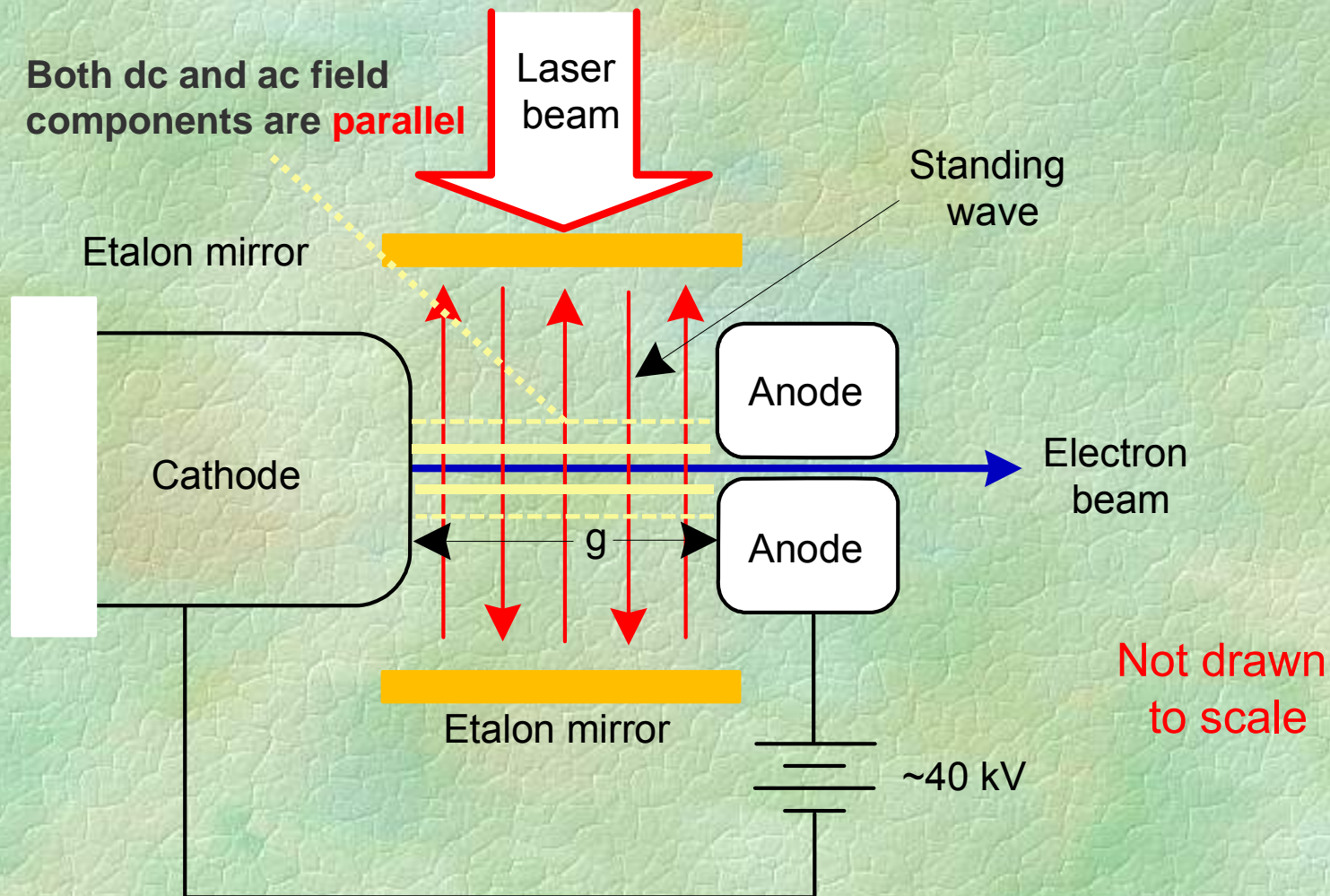
Solution: We need a *combination of ac and dc field* such that they both control the emission from the cathode. This way bunches are generated at the cathode. But the energy of each electron reaching the anode is determined by the dc alone. Train duration is set by the ac duration. Concept works in the microwave regime and needs to be adapted to optical wavelengths.

Optical Injector – Basic Operation



- Both E_{DC} and E_{AC} , are slightly larger than 1/2 value needed for onset of field emission.
- When laser field in same direction as DC field → emission occurs
- When laser field in opposite direction as DC field → emission suppressed.
- Micro-bunch length is determined by the duration both field components exceed the threshold value

Optical Injector – Schematic Setup



Optical Injector – Basic Model

- Field-emission cathode (Fowler-Nordheim)

$$J_{FN} = \frac{1.54 \times 10^{-6}}{\varphi} F^2 \exp \left[\frac{-6.83 \times 10^7 \varphi^{\frac{3}{2}} f(y)}{F} \right]; y = \frac{3.79 \times 10^{-4} \sqrt{F}}{\varphi}$$

$F = \beta E$

- Enhancement factor

- Ignoring space-charge

$$\frac{d^2 z_i}{dt^2} = \frac{e}{m} [E_{DC} + E_{AC} \cos(\omega t)]$$

- Time T_{tr} for electron to traverse gap (g)

$$g = \frac{e}{m} \left\{ E_{DC} \frac{1}{2} T_{tr}^2 + \frac{1}{\omega^2} E_{AC} \left[1 - \cos(\omega T_{tr}) \right] \right\}$$

- Mono-energetic e -beam, 2nd term on right to be zero

$$\omega T_{tr} = 2\pi n_0$$

Optical Injector – Basic Model

- To zero order, *charge shielding* tends to reduce field at cathode

$$E_{DC} \rightarrow E_{\text{eff}} = E_{DC} - \frac{eN_{el,AK}}{2\epsilon_0 A}$$

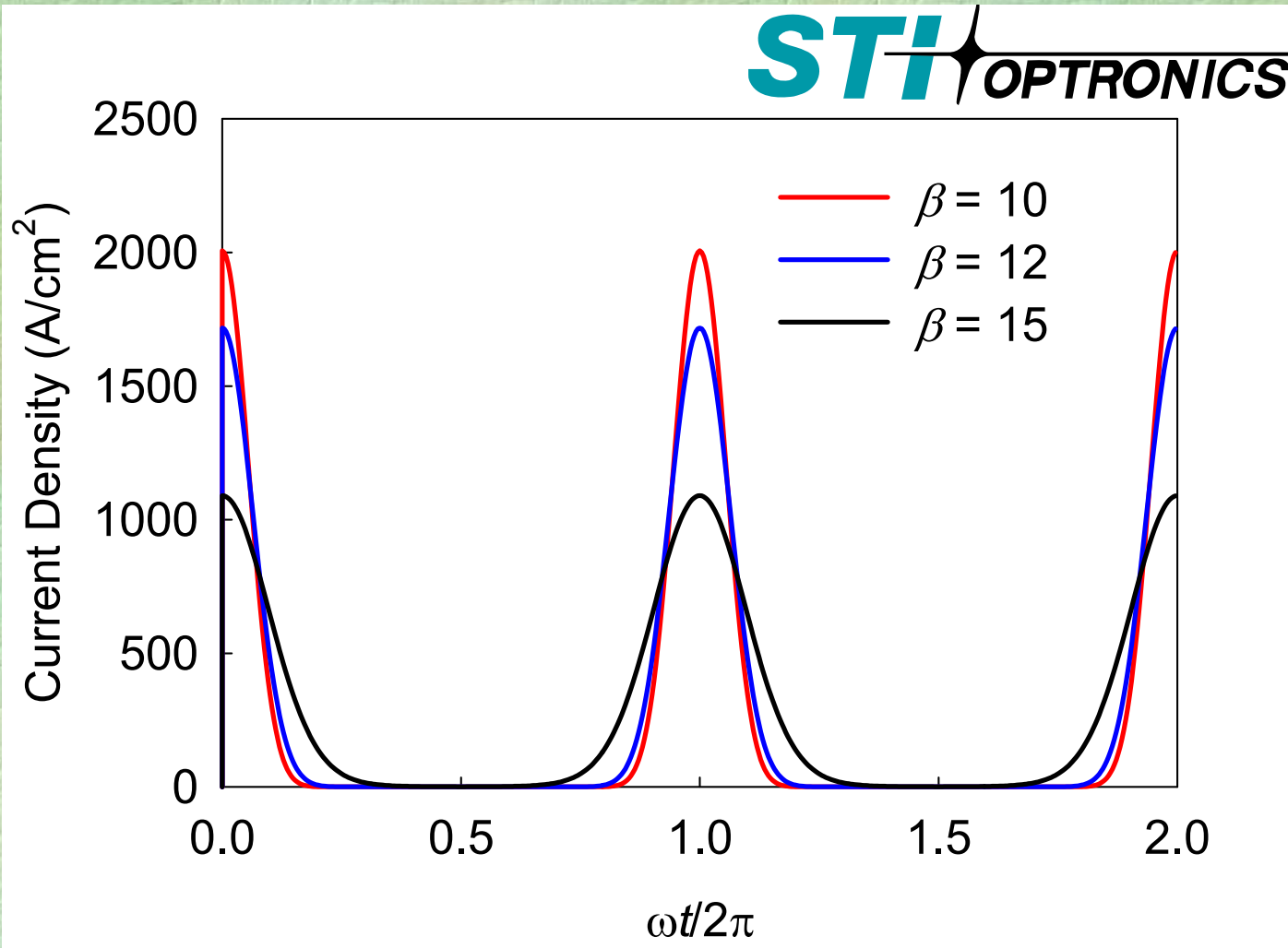
average number of electrons in gap $N_{el,AK} \approx$ (Number of electrons in single micro-bunch) \times (Number of micro-bunches in gap)

- Charge per unit surface (A) in A-K gap given by

$$\frac{N_{el,AK}}{A} = \frac{10^4}{e} n_0 \int_{0.5\lambda/c}^{1.5\lambda/c} dt J_{FN} \left\{ \frac{\beta}{100} \left[\frac{V_{DC}}{g} - \frac{eN_{el,AK}}{2\epsilon_0} + E_L \cos(\omega t) \right] \right\}$$

Optical Injector – Basic Model

For $E_{DC} = 40$ kV, $E_{AC} = 10^9$ V/m, $n_0 = 940$, $g = 996$ μm

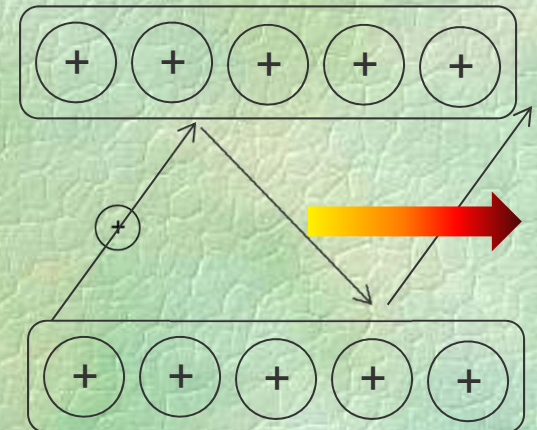


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Channeling Radiation – Essentials

- Kumachov (1976): “It is predicted that there can be a new type of radiation of relativistic channeled particles. A possibility of using this radiation in physics is indicated, in particular, for creating a nuclear γ -laser “.
- Classically: the particle bounces back and forth between the symmetry planes of the lattice and it generates radiation.
- QM: Relativistic particles are not affected in the *longitudinal* direction. However, in the *transverse* direction the dynamics is determined by a periodic potential – discrete states. The lowest is populated by particles moving *parallel* to the planes. The higher states are populated by particles which have some transverse momentum. A particle may drop from a high energy state to a lower one, emitting in the process a photon. In this framework, stimulated emission is feasible.



M.A. Kumakhov, Phys. Lett. A 57, 17 (1976)

Channeling Radiation – Proposed Paradigm

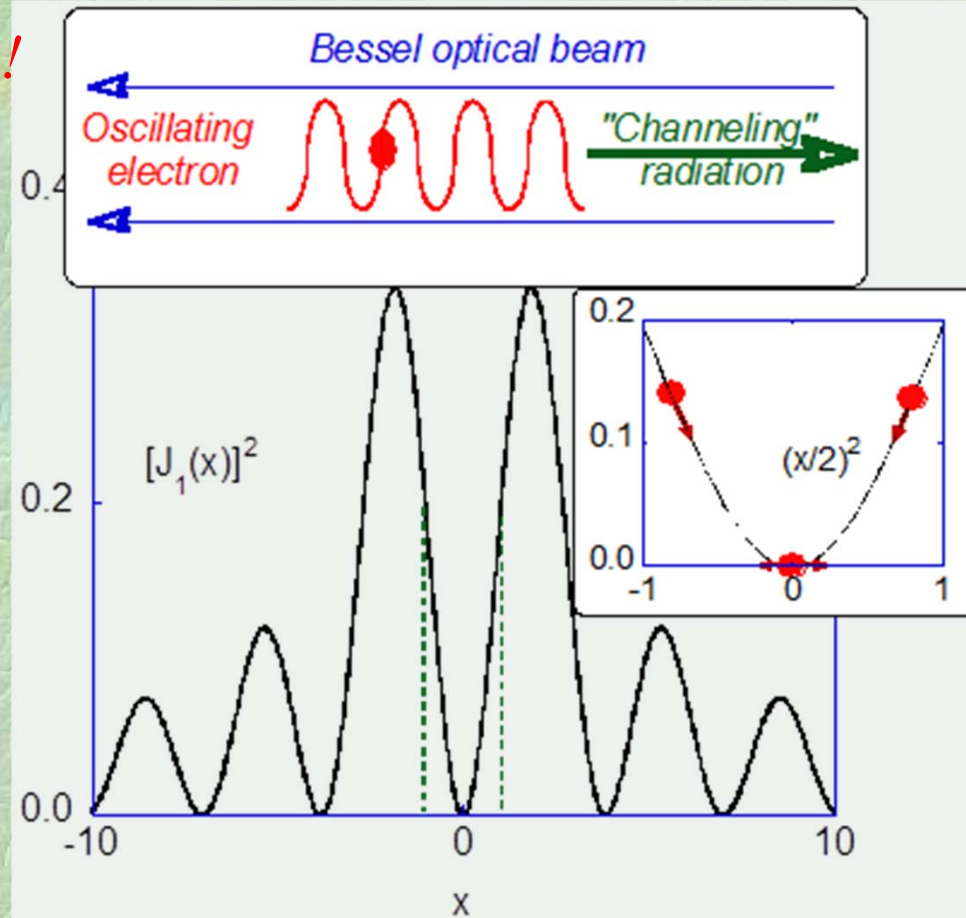
Channeling Radiation w/o crystal ?!

- Replace the solid-state crystal with an anti-propagating, radially polarized **Bessel beam**

- According to Maxwell's stress tensor the radial **force density** is

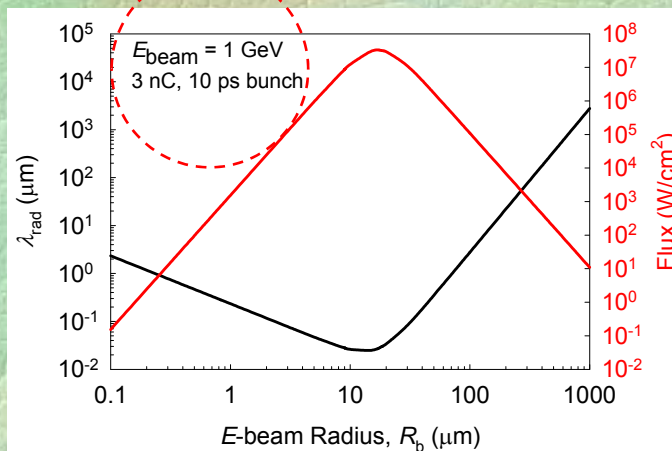
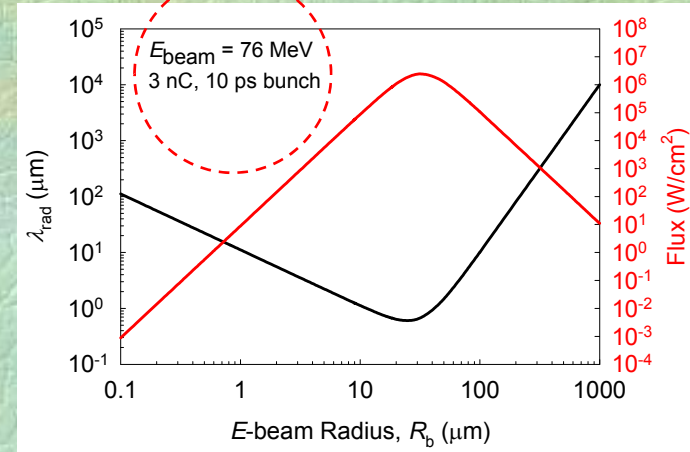
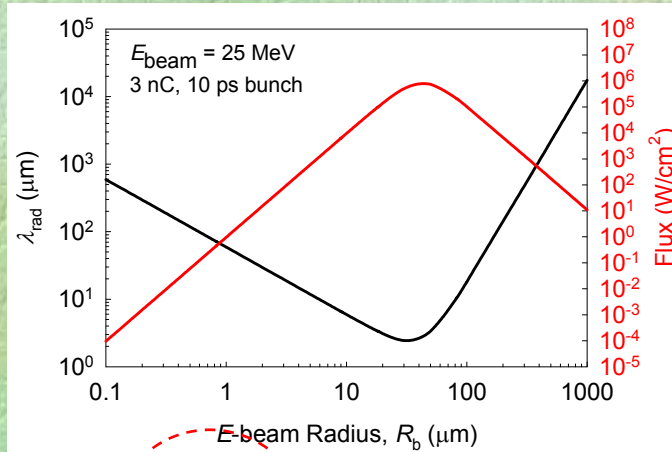
$$\langle f_r \rangle = - \left[\frac{\epsilon_0}{8} E_L^2 \left(\frac{\omega_L}{c} \right)^2 \sin^2 \theta_0 \right] r$$

$$\frac{d^2 x}{dt^2} \simeq - \left[\frac{1}{8} \frac{\epsilon_0 E_L^2}{mc^2 \gamma n_{\text{el}}} \omega_L^2 \sin^2 \theta_0 \right] x \equiv -\Omega^2 x$$



Channeling Radiation – Non-coherent

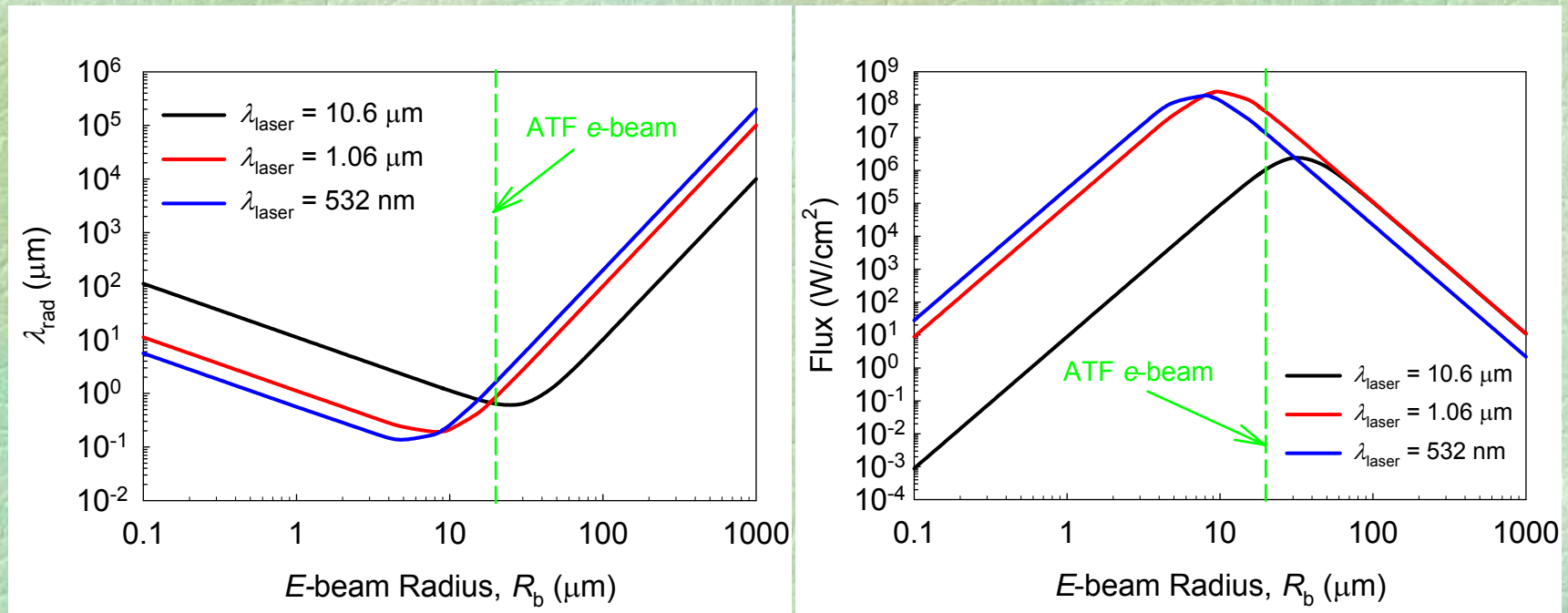
- $E_L = 10^9$ V/m (42 MW), $\lambda_{\text{laser}} = 10.6$ μm



- 25 MeV beam (ATF lowest energy) generates mid-IR at ~ 1 MW/cm^2
- 76 MeV beam (ATF highest energy) generates visible-NIR at > 1 MW/cm^2
- 1 GeV energy generates soft x-rays at > 10 MW/cm^2

Channeling Radiation – Non-coherent

- $E_{\text{beam}} = 76 \text{ MeV}$, $\tau_{\text{el}} = 10 \text{ ps}$, and $q_{\text{el}} = 3 \text{ nC}$ (corresponding to ATF e-beam), and $E_L = 10^9 \text{ V/m}$ (42 MW)



- Shorter laser wavelength tends to yield shortest emitted wavelength and highest flux

Summary

- The unique combination of laser and e-beam at ATF facilitates to test novel paradigms.
- In the present talk I revealed past experience and shared with you possible experiments that may be performed at ATF-II:
 1. Active Medium Two-beam Accelerator. Cherenkov wake amplification -> saturation. Acceleration in linear regime to compensate beam loading or at saturation when beam loading is weak. Rabi trapping and acceleration.
 2. Optical Injector – density modulated train of electron-bunches. The gap is chosen such that the transit time is an integer number of laser periods.
 3. Channeling radiation result of interaction of e-beam with Bessel-beam. Contrary to Inverse Compton scheme, the emitted wavelength is determined by the intensity of the laser. Opens a variety of possibilities: THz regime -> Soft X-ray

ATF-III ? A personal view

- Current design is biased towards not structure based schemes
- There are several essentials for a *structure-based* ATF :
 - # An optical electron injector (CO₂ – based) .
Micro-bunches of a fraction of the wavelength ($<\lambda/4$).
Periodicity λ or larger.
Charge 1,000-100,000e in one micro-bunch
 - # “Know-how” to actually make dielectric structures
 - # Cold-test dielectric structure.
 - # Low emittance (nm x rad) beam e.g. electron microscope
or Van Der Graff to test beam insertion, transport,
radiation generation.